Humans do not evidence choice biases in simple discrimination tasks.

Daniel Linares[a] and Joan López-Moliner[a,b].

[a] Department of Cognition, Development and Educational Psychology.
[b]Institut de Neurociències (UBneuro)
Universitat de Barcelona
Passeig de la Vall d'Hebron 171
08035 Barcelona, Spain

Corresponding author: Daniel Linares (danilinares@gmail.com)

Abstract

Choice behavior in detection tasks demonstrates that perceptual decision-making not only depends on sensory evidence, but also on choice biases: the tendency to choose one alternative over the others independently of the sensory evidence. To assess whether choice biases pervade other perceptual decision scenarios, we asked humans to perform a simple common perceptual discrimination task with two symmetric alternatives. We found that participants did not choose the two alternatives equally often, which is consistent with the occurrence of choice biases, but also with the occurrence of sensory biases. To test these possibilities, participants performed the task reversing the mapping between perception and the category of the alternatives. With this simple manipulation, participants reversed the frequency of choosing the two alternatives, which supports that the biased choice behavior was caused by biased sensory evidence. We also found consistent estimates of the sensory biases using a task with two asymmetric alternatives. Perceptual decision-making in simple tasks, thus, might be entirely based on the representation of sensory information.

Keywords: Decision-making, perception, choice biases, discrimination.

Introduction

Perceptual decision-making is the act of choosing an action from a set of alternatives based on sensory evidence [1–4]. Understanding its principles is important as many of the choices that an organism makes are based on sensory evidence. Sensory evidence, however, is not the only component in perceptual decision-making. Choice behavior in detection tasks, in which a decision-maker classifies stimuli as a *present* or *absent* signal [4], demonstrates that perceptual decision-making also depends on choice biases: the tendency to choose one alternative over the others, independently of the sensory evidence [2–5]. For example, when deciding whether the approaching person on the street is an acquaintance or not, an individual afraid of greeting an unknown person would more likely classify the approaching person as a stranger. Choice biases in these situations can be readily estimated by the frequency of false alarms: how often the signal is chosen as been present (acquaintance) while it is absent (stranger) [2–5]. To what extent choice biases pervade other perceptual scenarios is unknown [2].

A common simple perceptual decision situation consists in classifying, using two alternatives, stimuli that carry similar levels of signal relative to a neutral point [6–10]. One might need to decide, for example, whether a canvas is tilted clock or counterclockwise, an obstacle in the middle of the road is closer to the left or right border, or a car is drifting leftward or rightward. Whether choice biases occur in these discrimination tasks is unknown. A major problem in identifying them is that any tendency to choose one alternative more often could be attributed to choice biases, but also to the existence of asymmetries in the sensory representation [2,11]. To get around this difficulty, here we tested how choice behavior was affected by a simple manipulation that consisted in instructing decision-makers to reverse the mapping between perception and the category of the alternatives.

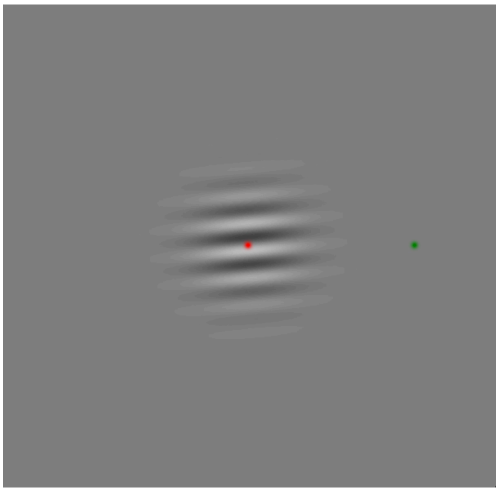

Figure 1. Illustration of the stimulus used in the experiment. The green dot was only displayed for illustration on a few trials before the experiment, but not during the experiment.

Results

On each trial, the orientation of a grating centered on a fixation point was chosen randomly from a range centered around the horizontal orientation. Participants judged whether the grating was pointing down or up (by pressing the *down* or *up* arrow keys on a keyboard) relative to a reference that we asked them to imagine placed on the right at the same height of the fixation point (green dot in figure 1, not shown in the experiment). Down and up choices correspond to clockwise and counterclockwise orientations relative to horizontal although we avoided this terminology when instructing participants.

Figure 2a shows the probability of clockwise (down) responses against the orientation of the grating and the corresponding psychometric fits [2,4] (green symbols, *supplementary material, models*). For all participants, but participant 6, the orientation that results in 50% probability of clockwise responses—which we will refer as the point of non-discrimination (PND)—was significantly different from horizontal (the confidence intervals did not include 0, *Methods*). Participants 1 and 5 decided more often that the grating was pointing up and participants 2, 3 and 4 that it was pointing down. Asymmetric choice behaviors like this have been shown before [12]. What causes them? One possibility is that participants show choice biases to select either the down or up alternative or press one of the buttons [2,3,11]; this might occur, for example, when participants are unsure about whether the grating is horizontally deviated [11]. Another possibility, however, is that the sensory evidence is biased, that is, the perceived horizontality of the grating corresponds to different orientations for different participants. A third possibility is that both sensory and choice biases occur.

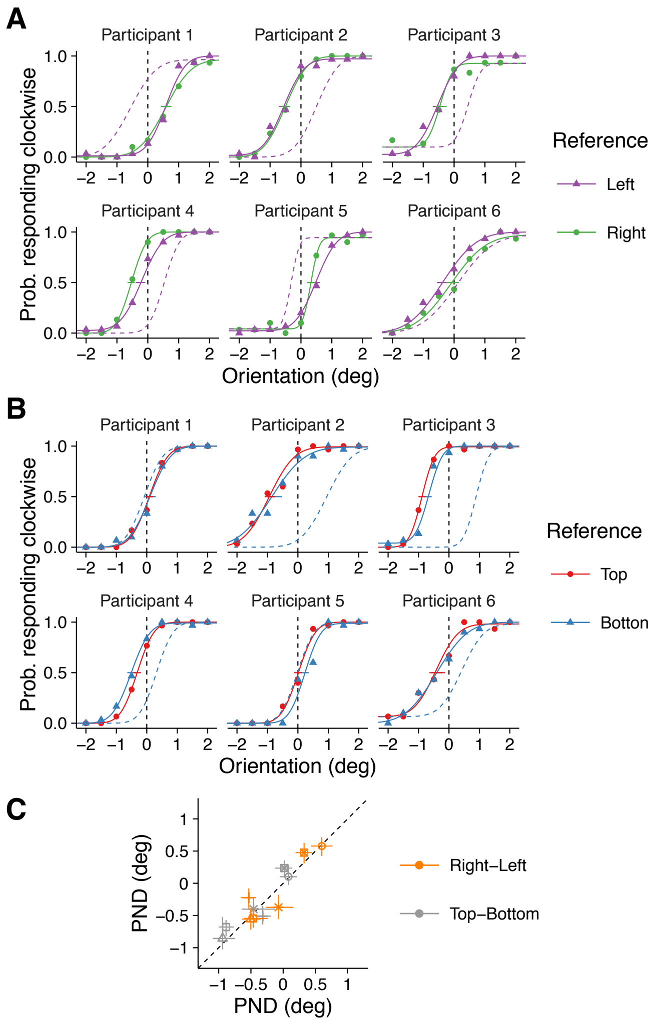

Figure 2. Results for the two-alternative symmetric task. (A) Probability of giving a response consistent with clockwise against the orientation of the grating and where participants imagine the reference (right or left). Continuous lines show the psychometric curve fits. The dotted lines show the predicted psychometric curves for the left-reference condition if the shifts of the psychometric curves for the right-reference condition were caused by choice biases. The horizontal segments at probability 0.5 show the confidence intervals for the PNDs. The PNDs are given by the intersection of these segments with the psychometric curves. (B) Like (A), but for a situation in which participants imagine the reference on top or at the bottom. (C) The PNDs and their confidence intervals in (A) and (B) replotted against each other. For more details, see Methods and supplementary material, models.

To disentangle these possibilities, we presented the same stimuli (in other trials intermixed with the trials just described), but asked participants whether the grating was pointing down or up relative to an imaginary reference on the *left* (in each trial, we notified where they needed to imagine the reference before the presentation of the grating). This variation in the instructions was easy for the participants to understand and effectively reversed the mapping between perception and category of the alternatives. Let us consider the probability of choosing an alternative consistent with clockwise orientation (up, in this case) when participants imagined the reference on the left. This probability should coincide with the probability of choosing an alternative consistent with clockwise orientation when the reference was imagined on the right, if biased choice behavior was caused by sensory biases. It should be shifted symmetrically relative to 0 deg, if biased choice behavior was caused by choice biases (dotted line in figure 2a, see also *supplementary material, models*). Finally, it should be shifted, but not symmetrically, if biased choice behavior was caused by both sensory and choice biases (see also *supplementary material, models*).

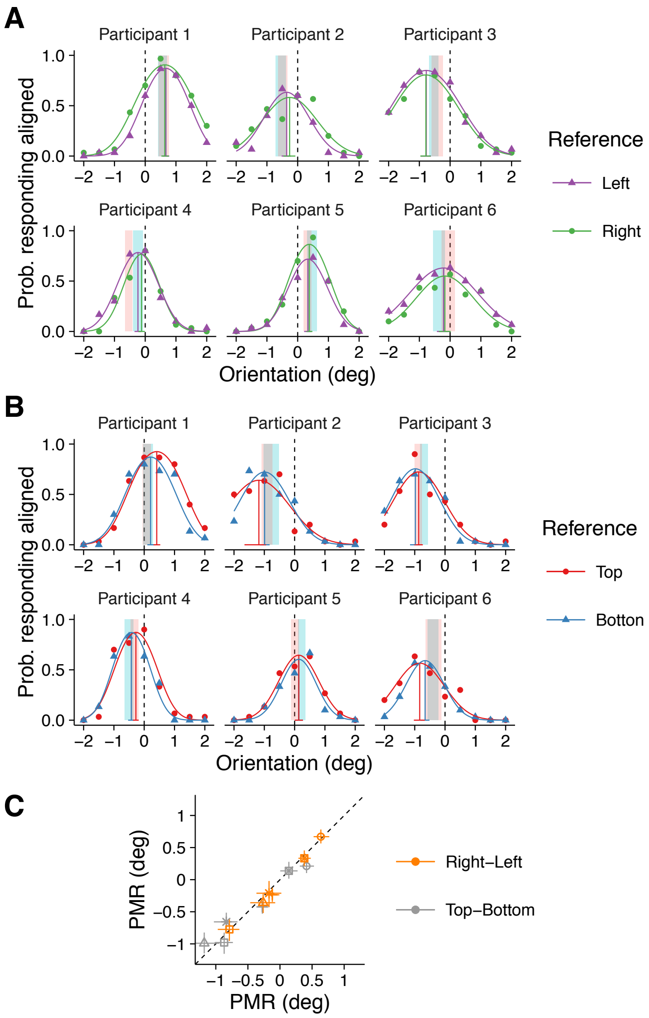

Figure 3. Results for the two-alternative asymmetric task. (A) Probability of responding aligned against the orientation of the grating and where participants imagine the reference (right or left). Continuous lines show the curve fits. The horizontal segments at probability 0 show the confidence intervals for the PMRs. The PMRs are given by the vertical lines of these segments with the psychometric curves. The colored areas replot the confidence intervals for the PNDs in figure 2. (B) Like (A), but for a situation in which participants imagine the reference on top or at the bottom. (C) The PMRs and their confidence intervals in (A) and (B) replotted against each other. For more details, see Methods and Supplementary Information.

Consistent with the hypothesis that biased choice behavior was caused by biased sensory evidence, the probability of clockwise responses depended very little on where the reference was imagined (figure 2a and 2c): for all participants but 4, the PND was not significantly different for the two response mappings (bootstrap statistics, *Methods*). For participant 4 the difference in PNDs was significant, but small indicating the presence of a small choice bias on top of a large sensory bias. Given that most PNDs were different from zero, the similar pattern of clockwise responses for the two conditions indicates that participants reversed the frequency of choosing the *down* and *up* alternatives and consequently the frequency of pressing the *down* and *up* keys. We obtained similar results when the grating was oriented around the vertical orientation and participants judged the orientation using the *right* and *left* keys relative to an imaginary reference on top or in the bottom (figure 2b and 2c). Overall, the correlation across PNDs was very large and significant (figure 2c; $r(10) = .93$, $p = 1 \times 10^{-5}$).

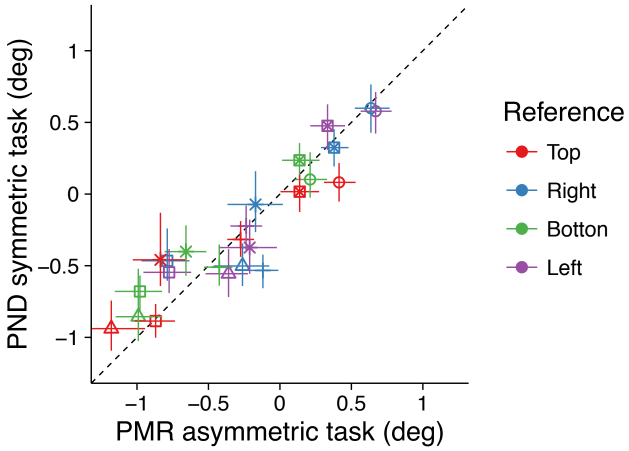

Figure 4. The PNDs in figure 2 plotted against the PMRs in figure 3 (the segments corresponds to the confidence intervals).

It could be argued that participants were not biased to favor the down or up alternative (or right and left) or one of the buttons, but instead biased to choose the alternative consistent with *clockwise* or *counterclockwise* orientation. If so, the biases would not be preserved if the perceptual task had two choices not directly related to the clockwise and counterclockwise alternatives. To test this prediction, in some other trials—intermixed with the previous trials—we asked participants to imagine a reference on the right, left, bottom or top and perform a two-alternative *asymmetric* choice task consisting in indicating whether the grating was aligned or not with the imagined reference. For this task, we characterized biases in choice behavior by estimating the orientation that maximized the probability of *aligned* responses (point of maximum response PMR, *supplementary material*). Consistent with the results using the symmetric task, we found the following results: the PMR was significantly different from zero for many participants (figure 3); for gratings presented around the horizontal and vertical orientation, for all participants but 1 and 4 (for which the difference was small, but significant for the vertical orientation) the PMRs were independent of the location of the imagined reference (figure 3). The correlation across PMRs was very large and significant (figure 3c; $r(10) = .98$, $p = 3 \times 10^{-8}$). Critically, we found a good agreement between the measures of biased choice behavior for symmetric (PNDs) and the asymmetric tasks (PMRs): from the 24 measures, 17 were not significantly different across tasks (figure 3a and 3b). For 7 the difference was significant (bootstrap statistics, *Methods*), but relatively small. Overall, the correlation of measures of biased choice behavior across tasks was very large and significant (figure 4; $r(22) = .93$, $p = 9 \times 10^{-11}$). The preservation of the biases in the asymmetric task supports that the biased choice behavior in the symmetric task is caused by biased sensory evidence with little contribution of choice biases.

Discussion

We showed that in a common orientation discrimination task with two symmetric alternatives, decision-makers often favor one alternative. Changing the stimulus-response mapping and testing a task with two asymmetric alternatives, we revealed that the preference for one alternative likely reflects biased sensory evidence. Our experiment does not bare the cause of the bias. One possibility is that participants' head is deviated from vertical [13], which predicts a bias consistent with a global rotation of the visual field. A significant correlation of our measures of biased choice behavior across orthogonal axes does not discard a contribution of this source (supplementary material, figure S1). However, the fact that this correlation is much smaller than the correlation that we found when considering measures along the same axis (figure 2c and 3c) indicates that this explanation cannot explain the sensory bias entirely. Another possible cause of the sensory bias is a biased representation of the stimulus in sensory areas [2]. Regardless, our experiment does show that choice biases, which in general are an integral component of the perceptual decision-making process [2,14–17], barely affect choice behavior in a simple discrimination task.

Perceptual discrimination tasks with two symmetric alternatives are often regarded as performance tasks [2,3,12,18]. If a stimulus has positive signal (e.g. rightward motion) relative to a neutral point (no net motion), but the decision--maker chooses the alternative consistent with negative signal (leftward motion), the response is considered an error (false alarm) [2,3,12,18]. Our results, however, suggest that those cases might reflect biased perception. Consequently, it might be inappropriate to consider them as errors and, in case feedback is given, provide a negative reward. Therefore, given that the physical and the perceptual neutral point do not necessarily coincide, discrimination tasks with two symmetric alternatives might need to be considered appearance tasks [19] and the point of of non-discrimination (PND) consistently referred as the point of subjective equality (PSE) [19].

Perceptual decision-making is often modeled using signal detection theory (SDT), a framework that has largely contributed to its understanding [1–4,18]. Conventional SDT regards discrimination tasks as performance tasks [2–4,18]. Accordingly, biased choice behavior is associated to the occurrence of choice biases, which are modeled as shifts of a criterion [2–4]—in the case of a discrimination task with two symmetric alternatives, from a neutral point [2,3]. Within this view, the reverse mapping that we devised should shift the criterion and result in a shift of the psychometric curve (*supplementary material, models*) that we did not observe (figure 2). To account for the lack of a shift in the psychometric curve, SDT can be expanded to include how the stimulus signal is transduced into sensory evidence (*supplementary material, models*). In this case, the biased choice behavior that we found corresponds to biased transductions of the sensory evidence (*supplementary material, models*).

Choice biases are sometimes associated to states in which the observer is uncertain [11,16,20], but SDT does not incorporate such cases: given the decision variable and a criterion, the decision rule to choose one alternative is unambiguous [4,11] (*supplementary material, models*). To include these uncertainty states, a high-threshold model has been proposed, which assumes that when the sensory evidence lies in some uncertainty range the decision-maker needs to guess [11]. Like SDT models, this high-threshold model is consistent with our results only if the biased choice behavior is caused by biased sensory evidence [11,20]. The high-threshold model, however, further requires that observers, when uncertain, guess the two alternatives equally often [11,20]. This additional assumption makes SDT a more parsimonious model for orientation discrimination.

In perceptual discrimination tasks with two symmetric alternatives, when humans are instructed to favor one alternative if unsure of their answer, their choice behavior is biased in the instructed direction [16]. We think that these choice biases can be understood in terms of SDT. When the symmetry of the task is not broken by the instructions, our results suggest that decision-makers divide the decision variable axis in two regions separated by a criterion consistent with the perceptual neutral point. If the decision variable for a given trial lies on the right region, decision-makers select a motor act such as pressing a *right* key; if it lies on the left region, they press the *left* key (*supplementary material, models*). When decision-makers are instructed to evaluate their confidence and favor one alternative when they are not confident, they might naturally divide the decision variable axis in three regions separated by two criteria around the perceptual neutral point—like in our asymmetric discrimination task [21] (*supplementary material, models*). In this case, when the decision variable lies on the right or left region, decision-makers would select the motor act like in the unbiased instructions case. But, when the decision variable lies in the central region, decision makers would select the motor act that they have been told to favor.

Discrimination tasks with two symmetric alternatives are commonly used to assess how perception is affected by contextual cues [22,23], but whether the context influences perception or causes biases to choose the cued alternative is debated [11,16,17,24–28]. Our results indicate that the two-alternative discrimination task is not fragile to choice biases suggesting that the task might be robust to measure perception in the presence of contextual cues [29]. Nevertheless, if the interest is to measure perceptual biases when one alternative is cued, it might be safer to use tasks in which potential choice biases are reduced or eliminated [3,11,28–30].

Our experiment tested global asymmetries in choice behavior, that is, preferences for one choice that are maintained across trials. Local asymmetries, in which the choice on a given trial is influenced by the stimuli or choices in previous trials, have also been reported [31]. Recent findings suggest that these local asymmetries might also be caused by sensory biases [32,33].

We confirmed the perceptual biases measured using the symmetric task with an asymmetric task in which participants indicated whether the stimulus signal was consistent with the neutral point. The agreement between tasks contrasts with the disagreement of the symmetric and asymmetric counterparts in the temporal domain [34–36]—temporal order and simultaneity judgments—opening the possibility that decision-making for time perception is affected by choice biases [35,37,38].

Methods

The study was approved by the local ethical committee of the University of Barcelona and followed the requirements of the Helsinki convention. Six participants, who did not know the hypothesis of the experiments, provided written consent to perform the experiments.

Stimuli—generated using PsychoPy [39]—were displayed on a Sony G520 CRT screen (40 cm width and 30 cm height; 60 Hz refresh rate) and viewed from a distance of 57 cm in a dark room. They consisted in a Gabor patch (standard deviation (sd) of the Gaussian envelope: 1.33 degrees of visual angle (dva); maximum luminance: 79 cd/m^2) and a red Gaussian blob (sd: 0.1 dva; maximum luminance: 19 cd/m^2) on top of it that participants were asked to fixate during the experiment. Stimuli were presented against a uniform circular grey background (diameter: 25 dva; luminance: 43 cd/m^2) that was displayed in a black background (luminance: 0.2 cd/m^2). The verticality of the Gabor was calibrated using a pendulum.

Participants performed 6 blocks of 360 trials. In each block, 8 conditions were randomly intermixed across trials. In each trial, before the Gabor was presented, a text message informed participants about the condition. A *right: up or down?* message instructed participants to imagine a reference on the right (at the same height of the fixation point) and respond whether the Gabor was pointing down (clockwise) or up (counterclockwise) relative to it. A *left: up or down?* message instructed participants to imagine a reference on the left and respond whether the Gabor was pointing down (counterclockwise) or up (clockwise). For these conditions, the orientation of the Gabor was chosen randomly from a range centred around horizontal orientation (from -2 to 2 deg in steps of 0.5 deg) according to the method of constant stimuli [19]. The *up: right or left?* and the *down: right or left?* messages provided parallel instructions for imaginary references on top and bottom. For these conditions the orientation was centered around vertical orientation. Participants used the arrow keys to respond. A *right?* message instructed participants to imagine a reference on the right and respond whether the Gabor was aligned with it (pressing *m* key) or not (pressing *n* key). A *left?*, *up?* and *down?* provided parallel instructions for references in other locations. The messages were available until participants pressed the spacebar. The Gabor was presented for 100 ms, 500 ms after the keypress.

Before the experiment, to facilitate the understanding of the instructions, a green dot (sd: 0.1 dva; maximum luminance: 29 cd/m^2) acting as a reference was displayed for 5 to 10 trials at the top, bottom, left or right of the Gabor patch at a distance of 6 dva from the center of the fixation point (figure 1). During the experiments, the green dot was not displayed.

Curve fits were estimated by maximum likelihood. Statistics for the PNDs and PMRs were calculated using 1000 non-parametric bootstrap samples of the PNDs and PMRs. We obtained the confidence intervals choosing the 2.5% and 97.5% percentiles and assessed whether two PNDs or PMRs were different by subtracting their samples and considering whether the difference was within the 2.5% and 97.5% percentiles. All the data analysis was done using the *quickpsy* R library [40]. The data and the code to do the statistical analysis and create the figures is available at https://github.com/danilinares/2016LinaresLopezmoliner.

Acknowledgments

The research was funded by the Catalan government (2014SGR-79) and Ministry of Economy and Competition of the Spanish government (PSI2013-41568-P).

Supplementary material, figures.

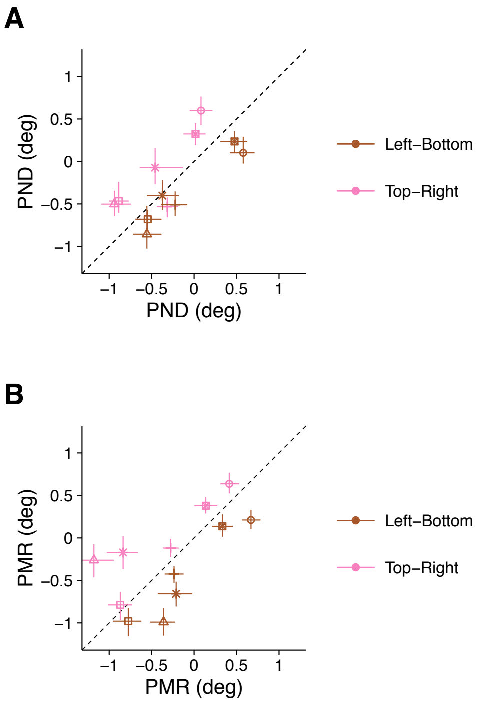

Figure S1. (A) The PNDs in figure 2 replotted to show the PNDs when the reference was imagined on the left against the PNDs when the reference was imagined on the bottom and the same for references imagined on top and right (r(10) = .71, p = .01). (B) Like (A), but for the PMRs (r(10) = .66, p = .02).

Supplementary material, models.

Modeling the two-alternative symmetric choice task

The two-alternative symmetric choice task can be modeled using a simple SDT model that includes how the stimulus signal is transduced into sensory evidence [11,20,38,41]. The sensory evidence r is considered a random variable normally distributed with mean $\overline{r}$ linearly related to the stimulus signal (i. e. orientation) θ

$$\overline{r} = a\theta + b.$$

Given the assumption of normality, the sensory evidence can be used as the decision variable [4]. Without loss of generality, it could be assumed that the variance of r is 1 because a takes already into account the variability of the sensory evidence. Biased sensory evidence corresponds to $b \neq 0$. For any given trial, a simple decision rule consists in choosing one of the alternatives ($z = 0$; clockwise, for example) if the sensory evidence is larger than a criterium c and the other alternative ($z = 1$; counterclockwise, for example) otherwise. Choice biases correspond to $c \neq 0$. Across trials the probability of choosing one of the alternatives as a function of the stimulus signal (the psychometric function) is given by

$$p\left(z = 0 | r\left(\theta\right)\right) = \frac{1}{\sqrt{2\pi}} \int_{c}^{\infty} e^{\frac{(r - a\theta - b)^2}{2}} \, dr = \Phi\left(a\theta + b - c\right)$$

where Φ is the standard cumulative normal distribution. This psychometric function, which corresponds to a cumulative normal distribution with mean $a^{-1}(c-b)$ and variance a^{-2}, is the function that we fitted to the data. We also allowed lapses to improve the goodness-of-fit [2,40,42] although these non-sensory driven responses at high stimulus signal were minimal (figure 2).

In general, given that Φ depends on $b-c$, it is not possible to distinguish sensory from choice biases. Let us consider, however, the situation in which the participant chooses between the up or down alternatives. A criterion c associated to a bias to choose responses consistent with clockwise orientation when the reference is on the right corresponds to a criterion $-c$ when the reference is on the left, which should result in a shift of the psychometric function $\Phi(a\theta+b+c)$. If biases decisions were entirely caused by choice biases ($b=0$), the psychometric curves would shift symmetrically relative to 0 (dotted lines in figure 2). If the biases decisions were entirely caused by sensory biases ($c=0$), the psychometric curves would be independent of the location of the reference. Non-symmetric shifts relative to 0 would indicate the presence of both sensory and choice biases.

Modeling the two-alternative asymmetric choice task

We considered that the sensory evidence is transduced as in the two-alternative symmetric choice task, but the decision rule consists in choosing the *aligned* alternative ($z=0$) when the evidence lies within c and $-c$ and the misaligned alternative ($z=1$) otherwise. Therefore, the probability of choosing one of the alternatives as a function of the stimulus level is given by

$$p\left(z=0|r\left(\theta\right)\right)=\frac{1}{\sqrt{2\pi}}\int_{-c}^{c}e^{\frac{(r-a\theta-b)^2}{2}}\,dr=\Phi\left(c-a\theta-b\right)-\Phi\left(-c-a\theta-b\right)$$

which is the function that we fitted to the data.

References

1. Gold, J. I. & Shadlen, M. N. 2007 The neural basis of decision making. *Annu. Rev. Neurosci.* **30**, 535–574.

2. Gold, J. I. & Ding, L. 2013 How mechanisms of perceptual decision-making affect the psychometric function. *Prog. Neurobiol.* **103**, 98–114.

3. Carandini, M. & Churchland, A. K. 2013 Probing perceptual decisions in rodents. *Nat. Neurosci.* **16**, 824–831.

4. Green, D. M. & Swets, J. A. 1966 Signal detection theory and psychophysics. 1966. *New York* **888**, 889.

5. Sridharan, D., Steinmetz, N. A., Moore, T. & Knudsen, E. I. 2014 Distinguishing bias from sensitivity effects in multialternative detection tasks. *J. Vis.* **14**. (doi:10.1167/14.9.16)

6. Jazayeri, M. & Movshon, J. A. 2007 A new perceptual illusion reveals mechanisms of sensory decoding. *Nature* **446**, 912–915.

7. Mareschal, I., Dakin, S. C. & Bex, P. J. 2006 Dynamic properties of orientation

discrimination assessed by using classification images. *Proc. Natl. Acad. Sci. U. S. A.* **103**, 5131–5136.

8. Milner, A. D., Brechmann, M. & Pagliarini, L. 1992 To halve and to halve not: an analysis of line bisection judgements in normal subjects. *Neuropsychologia* **30**, 515–526.

9. Newsome, W. T. & Paré, E. B. 1988 A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *J. Neurosci.* **8**, 2201–2211.

10. Tadin, D., Lappin, J. S., Gilroy, L. A. & Blake, R. 2003 Perceptual consequences of centre–surround antagonism in visual motion processing. *Nature* **424**, 312–315.

11. García-Pérez, M. A. & Alcalá-Quintana, R. 2013 Shifts of the psychometric function: distinguishing bias from perceptual effects. *Q. J. Exp. Psychol.* **66**, 319–337.

12. Gold, J. I., Law, C.-T., Connolly, P. & Bennur, S. 2008 The relative influences of priors and sensory evidence on an oculomotor decision variable during perceptual learning. *J. Neurophysiol.* **100**, 2653–2668.

13. Tarnutzer, A. A., Bockisch, C., Straumann, D. & Olasagasti, I. 2009 Gravity dependence of subjective visual vertical variability. *J. Neurophysiol.* **102**, 1657–1671.

14. Peters, M. A. K., Ro, T. & Lau, H. 2016 Who's afraid of response bias? *Neuroscience of Consciousness* **2016**, niw001.

15. Luo, T. Z. & Maunsell, J. H. R. 2015 Neuronal Modulations in Visual Cortex Are Associated with Only One of Multiple Components of Attention. *Neuron* **86**, 1182–1188.

16. Morgan, M., Dillenburger, B., Raphael, S. & Solomon, J. A. 2012 Observers can voluntarily shift their psychometric functions without losing sensitivity. *Atten. Percept. Psychophys.* **74**, 185–193.

17. Mather, G. & Sharman, R. J. 2015 Decision-level adaptation in motion perception. *R Soc Open Sci* **2**, 150418.

18. Dayan, P. & Abbott, L. F. 2001 *Theoretical neuroscience*. Cambridge, MA: MIT Press.

19. Kingdom, F. A. A. & Prins, N. 2016 *Psychophysics: A Practical Introduction*. Elsevier Science.

20. García-Pérez, M. A. & Peli, E. 2014 The bisection point across variants of the task. *Atten. Percept. Psychophys.* **76**, 1671–1697.

21. Wickens, T. D. 2001 *Elementary Signal Detection Theory*. New York: Oxford University Press.

22. Carrasco, M., Ling, S. & Read, S. 2004 Attention alters appearance. *Nat. Neurosci.* **7**, 308–313.

23. Schwartz, O., Hsu, A. & Dayan, P. 2007 Space and time in visual context. *Nat. Rev. Neurosci.* **8**, 522–535.

24. Carrasco, M. 2011 Visual attention: the past 25 years. *Vision Res.* **51**, 1484–1525.

25. Störmer, V. S., McDonald, J. J. & Hillyard, S. A. 2009 Cross-modal cueing of attention alters appearance and early cortical processing of visual stimuli. *Proc. Natl. Acad. Sci.*

U. S. A. **106**, 22456–22461.

26. Schneider, K. A. 2011 Attention alters decision criteria but not appearance: a reanalysis of Anton-Erxleben, Abrams, and Carrasco (2010). *J. Vis.* **11**, 7.

27. Anton-Erxleben, K., Abrams, J. & Carrasco, M. 2010 Evaluating comparative and equality judgments in contrast perception: attention alters appearance. *J. Vis.* **10**, 6.

28. Jogan, M. & Stocker, A. 2012 A new 2AFC method for the comparison of stimuli that differ along multiple stimulus dimensions. *J. Vis.* **12**, 619–619.

29. Patten, M. L. & Clifford, C. W. G. 2015 A bias-free measure of the tilt illusion. *J. Vis.* **15**, 8.

30. Morgan, M. J. 2014 A bias-free measure of retinotopic tilt adaptation. *J. Vis.* **14**, 7–7.

31. Akaishi, R., Umeda, K., Nagase, A. & Sakai, K. 2014 Autonomous mechanism of internal choice estimate underlies decision inertia. *Neuron* **81**, 195–206.

32. Fischer, J. & Whitney, D. 2014 Serial dependence in visual perception. *Nat. Neurosci.* **17**, 738–743.

33. St John-Saaltink, E., Kok, P., Lau, H. C. & de Lange, F. P. 2016 Serial Dependence in Perceptual Decisions Is Reflected in Activity Patterns in Primary Visual Cortex. *J. Neurosci.* **36**, 6186–6192.

34. Love, S. A., Petrini, K., Cheng, A. & Pollick, F. E. 2013 A psychophysical investigation of differences between synchrony and temporal order judgments. *PLoS One* **8**, e54798.

35. Linares, D. & Holcombe, A. O. 2014 Differences in perceptual latency estimated from judgments of temporal order, simultaneity and duration are inconsistent. *Iperception* **5**, 559–571.

36. van Eijk, R. L. J., Kohlrausch, A., Juola, J. F. & van de Par, S. 2008 Audiovisual synchrony and temporal order judgments: effects of experimental method and stimulus type. *Percept. Psychophys.* **70**, 955–968.

37. Shore, D. I., Spence, C. & Klein, R. M. 2001 Visual prior entry. *Psychol. Sci.* **12**, 205–212.

38. Schneider, K. A. & Bavelier, D. 2003 Components of visual prior entry. *Cogn. Psychol.* **47**, 333–366.

39. Peirce, J. W. 2007 PsychoPy—Psychophysics software in Python. *J. Neurosci. Methods* **162**, 8–13.

40. Linares, D. & López-Moliner, J. In press. quickpsy: An R Package to Fit Psychometric Functions for Multiple Groups. *journal.r-project.org*

41. Schneider, K. A. & Komlos, M. 2008 Attention biases decisions but does not alter appearance. *J. Vis.* **8**, 3.1–10.

42. Wichmann, F. A. & Hill, N. J. 2001 The psychometric function: I. Fitting, sampling, and goodness of fit. *Percept. Psychophys.* **63**, 1293–1313.